Overview of Wireless Sensing

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***Abstract*—Throughout history there has been a lot of research on wireless technology, mainly for communication purposes. Another purpose is the remote sensing of objects and activities, to which we refer as wireless sensing. In the past decade a significant amount of research has been performed concerning wireless sensing, with the technology being applied to many areas such as the detection of human presence, gesture detection, agriculture, law enforcement, and healthcare. In this overview we present a number of wireless sensing solutions and analyse them according to their history, application, wireless technology, and processing technique. Furthermore, wireless sensing is compared to alternative technologies. Finally, we also give an overview of the current challenges and possible future trends.**

I. INTRODUCTION

Every since the discovery of radio waves, numerous applications have been invented that make use of them. A common one is the use of radio waves in communication. Another is using electromagnetic waves for the detection, tracking, and identification of entities, and activities performed by those entities. This is what we refer to as *wireless sensing*, also called *sensorless sensing* [1].

In the literature there are numerous definitions related to the concept. A paper by Youssef et al. [2] talks about the need to detect, track, and identify entities in an environment through the use of Wi-Fi signals. Wang et al. [3] talk in a more general fashion about using RF signals to obtain various amounts of information about a range of different objects. Wikipedia talks about Wi-Fi Sensing [4] where existing Wi-Fi signals are used to detect events.

Given that the exact definitions may vary from source to source, we will interpret the idea of wireless sensing in a broad sense. We will consider any type of wireless signal, no matter the frequency or technology, and we will consider any phenomenon or entity that is targeted. The only requirement is that the sensing itself is performed through the use of wireless signals. This is similar to the idea used by Woyach et al. [1].

This paper is inspired by a lecture on wireless sensing that was given as part of the Topics in Computer Networks course at the University of Antwerp. In this lecture, that was given by Rafael Berkvens, a brief overview of the field was given. The sensing disciplines of localisation, detection, and identification were outlined, and information was given on technologies such as measuring attenuation, angle-of-arrival, fingerprinting, etc. Finally, a number of use cases were given such as the localisation of containers, vehicle tracking, and plant growth.

In this paper we will give a broad overview of wireless sensing in a way that is more expansive than the previously mentioned lecture. We will try to remain as brief as possible when talking about things already covered in said lecture, but we will still include them for completeness.

We will give such an overview by considering multiple aspects of wireless sensing. We will start by going through the history of wireless sensing (Section II). Next we touch upon a number of applications (Section III). We will list a number of technologies (Section IV) and processing techniques (Section V) that make wireless sensing possible. To motivate the use of wireless sensing we compare it to possible alternatives (Section VI). In order to give a good perspective on the current state of the research we will give a number of challenges and future trends (Section VII). Finally we conclude this overview (Section VIII).

II. HISTORY

In order to place the use of wireless signals for sensing purposes in the right context, we will give an historical overview of the development of wireless technology related to sensing.

In 1864, James Clerk Maxwell theoretically proved the existence of electromagnetic waves. Later, in 1888, it was Heinrich Rudolf Hertz who performed experiments to confirm the presence of electromagnetic radiation in practice. Towards the end of the 19th century, Guglielmo Marconi made efforts to develop devices that were capable of wirelessly transmitting and receiving information, achieving a trans-atlantic transmission in 1901. The development of wireless communications continued throughout the 20th century resulting in commercial radio, television, and later also digital cellular networks [5].

Aside from communications, electromagnetic radiation may also be used for remotely detecting objects. During the experiments that Marconi conducted at the end of the 19th century, he noticed that some radio waves were being reflected by objects. In a 1922 paper he wrote that such reflections could be useful to detect ships and to prevent collisions. It was already in 1904 however that Christian Hülsmeyer demonstrated the use of radio waves to prevent ship collisions [6].

The development of radar was accelerated in the 1930s in different countries, the reason being heightened political tensions and many countries anticipating that a radar system deployed on a large scale could pose a strategic advantage. The result of this developmental effort was the realisation of radar systems in multiple countries, with success and strategic impact differing from case to case. In the United Kingdom this resulted in the Chain Home radar system [6].

After the Second World War, radar underwent additional developments, with more applications being found. During the Cold War many nations developed nuclear weapons and the means to deliver them using missiles. To provide political and military decision makers the opportunity to respond to a nuclear attack early-warning radars were developed, some of which even possessed over-the-horizon capabilities [6], [7]. Radar systems may also be used for civilian purposes. So-called airport surveillance radars were developed in the post-war years and are still being refined up until today. Such radars are used in the context of air traffic control to ensure safety in the airspace around airports [6]. Advances in digital signal processing technologies in the 1980s have also enabled the development of passive radars that do not transmit a signal of their own [8].

In the cold war efforts have been conducted to make aircraft less visible to enemy radar. This shows that it is possible to develop measures to counter the effectiveness of wireless sensing. Such efforts are targeted at limiting the radar cross section of an aircraft. This has resulted in the development of multiple aircraft types such as the U-2 spy plane, and the F-117 and B-2 bomber aircraft [9].

Such sensing efforts are not limited to detecting ships and aircraft, but may also be used to detect metal objects from up close. An early application was the detection of mines. To this end portable detectors were developed since the 1920s and deployed during the Second World War. After the war such devices were used for de-mining purposes. When a number of terrorist incidents occurred, the United States decided in 1972 to install metal detectors to provide airport security [10].

Another application of wireless sensing that has been developed in the Second World War, is the LORAN hyperbolic navigation system. This system uses radio beacons to allow pilots to determine the location of their aircraft. It was developed in the early 1940s with deployment commencing in 1942. The system was widely deployed, most notable in the Pacific Ocean theater due to the enormous distances and lack of useful navigation points [11].

More recently there has been a shift towards using wireless signals to detect the presence of humans. In 2006, Woyach et al. [1] introduced *sensorless sensing*, demonstrating that human motion influences signal strength. Shortly after in 2007, Youssef et al. [2] demonstrated that it is indeed possible to detect human presence and to locate humans using the received signal strength indicator [12].

In the last decade there has been rapid development in this field [13]. Recently, efforts are made to incorporate modern technologies such as the internet of things (IoT), sub-GHz frequencies, and 5G networks [14], [15], as well as deep learning [3], [15].

III. Applications

In some papers a general idea is given on what wireless sensing can be capable of. The applications of detecting, tracking, and identification are mentioned in [2] and [16]. In [17] Ma et al. mention that applications of wireless sensing may be divided into three categories: *detection*, which involves binary classification; *recognition*, which involves multi-class classification; and *estimation*, which involves obtaining quantity values.

Even though this provides a general idea about the usefulness of wireless sensing, we will give more concrete examples that are present in the literature.

A rather straightforward application is the detection of humans, facilitated by the fact that the presence of humans influences wireless signals [13]. This makes it possible to determine whether or not humans are present [16], and to estimate the amount of humans present [16], [18]. It is also possible to detect humans when there are obstructions (e.g. walls) between the human, the wireless transmitter, and the wireless receiver [19].

Another common application is the localisation and tracking of entities, which means that we will try to determine the position of the targeted entity [2]. Such localisation may both be indoors [13] or outdoors [14], [20]. The localisation may be performed by an external observer to locate a target [13], [20], or may be performed by the entity itself to find its own position [3], [11], [14]. A concrete example is the localisation of workers in a factory [15], which is necessary to prevent accidents between workers and robots.

The identification of humans or vehicles is also possible [16]. We can uniquely identify humans, due to the effects that the human body has on signal attenuation [16]. We may also apply more fine-grained gait analysis [13], [16], [21], or even analyse the unique breathing pattern of a person [22].

The gestures and activities that are performed by humans can also be analysed using wireless sensing technology. Such analysis can be used to differentiate between activities such as running, walking, sitting, or sleeping [13], [23]. It is also possible to differentiate between more fine-grained gestures such as mouth movements, keystrokes, and hand gestures [13], [22].

An important application of wireless sensing can be found in healthcare. Examples are the sensing of vital signs such as respiration and heart rate [13], [20]. It may also be used in clinical settings to diagnose walking problems by performing gait analysis [21]. Sleeping positions [22] and sleep apnea

[23] may be detected in order to identify sleeping problems. Finally, healthcare services can also be delivered at home or at an elderly care facility [22]. In order to facilitate this, wireless sensing can be used for fall detection as well as essential tremor detection [23], [24].

Finally, we will give two more examples to demonstrate that the applications of wireless sensing are wide and broad. The first is the use of RF signals to determine the moisture content of grain [25], where Nelson et al. used RF techniques to measure permittivity which correlates with the moisture content. A security related application is the sensing of explosives, chemicals, and weapons using terahertz (THz) signals [26]. Such materials can be detected because they have distinct radio signatures when exposed to THz signals, while uninteresting materials such as clothing and packaging are invisible [26].

IV. Wireless technologies

In this section, we will list a number of technologies and frequencies that may be used for wireless sensing purposes. We will also talk about the properties of the signals that are recorded.

In the literature there is mention of a wide range of frequencies that are utilised for sensing purposes. For example the LORAN navigation system operates on frequencies as low as 1.75 MHz [11], while Radar may use frequencies as high as 110 GHz [27]. More recent examples of sensing make use of sub-GHz bands [14], [18], [20], [28], making them compatible with signals generated by internet-of-things (IoT) signals [28]. If we look at Federici et al. [26] we see that even THz frequencies may be employed.

Aside the the wide range of frequencies, there is also a wide variety of technologies that may be employed. Many wireless sensing solutions make use of Wi-Fi signals [3], [13], [16], [19], [22], [23]. An important reason for the prevalence of Wi-Fi based solutions is that Wi-Fi is low-cost and prevalent in many environments [13]. It is also possible to re-use existing 5G signals [15]. An example of a technology that is not related to communications is radar, which is used both in older [27] and newer [13] applications. A downside of radar is that is requires specialised hardware [13]. Re-using existing communication signals has the advantage that such signals are widely available, and may be captured using off-the-shelf equipment [13].

Once the preferred technology and frequency is chosen for a solution, one can begin capturing the relevant signals in order to analyse them. There are multiple aspects of a signal that are suitable for analysis, such as the received signal strength (RSS). The RSS indicates the path loss $P(d)$ of wireless signals w.r.t. a certain distance d and can be derived using the Log-normal Distance Path Loss Model [13]:

$$P(d) = P(d_0) + 10 \cdot \gamma \cdot \log\left(\frac{d}{d_0}\right) + X_\delta$$

This formula can be applied in practice by taking into account the transmitted power, and some circuitry characteristics [29]. The use of RSS is widespread in the literature and is also available in many Wi-Fi devices [13], although it also applicable to wireless signals in general. However, RSS is course-grained since it is a single value for a packet, and it has also been shown to be instable [13]. This makes RSS an easy but also limited property to use for wireless sensing purposes.

A more fine-grained property of a wireless signal is the channel state information (CSI), which contains more detailed information such as phase and amplitude of each subcarrier of a signal [13]. This is useful since each subcarrier may be influenced in a different way, each subcarrier thus providing more information about the environment [13]. We can see the CSI as a vector $H = (H_1, \cdots, H_n)$, with H_i being the Channel Frequency Response for the i-th carrier [23]. If we transmit x and receive y, we can say that $y = Hx + n$, with H the CSI values, and n the noise [19]. From this, we can estimate H. The fact that CSI is more detailed than RSS has made it possible to more accurately sense humans [13]. The downside, however, is that CSI is not as widely available as RSS [23].

Some researchers utilise a form of radar called FMCW radar [13], [30] in order to obtain accurate measurements of human motion. This type of radar involves sweeping across a certain bandwidth during a certain amount of time, with k being the proportion of the two. We then measure the frequency shift Δf as the difference between the transmitted and the received frequency. We determine the time of flight Δt between the target and the transmitter using $\Delta t = \frac{\Delta f}{k}$. The distance can then be calculated as $d = c \cdot \Delta t$, where c is the speed of light [13], [30]. Compared to RSS and CSI, which are present in off-the-shelf Wi-Fi hardware, the FMCW radar requires specialised hardware [13].

Even though we have already introduced the FMCW radar, there exist other radar techniques that only measure the frequency shift without measuring the range [13], [21]. This technique may be used to detect movement, relying on the fact movement induces shifts in the frequencies of signals [13].

V. Processing techniques

In this section we will discuss techniques that can be used to process information captured by a wireless receiver, in order to use that information for wireless sensing purposes. A number of sources [12], [17] report that such techniques may be divided into two categories: model-based and pattern/learning-based.

The techniques that belong to the model-based category are based on the understanding of the mathematical relationship between signals, the environment, and the entities that are being observed [12]. There exist theoretical and statistical models [17].

Examples of the theoretical models are the Fresnel Zone Model, Angle of Arrival, Doppler, and the CSI-speed model. A characteristic of the theoretical models are that they are based on scientific knowledge and insight, such as physics [12], [17]. The statistical models on the other hand are based on empirical measurements and probability distributions. Examples are the Rician fading, Power Spectral Density, or the correlation of CSI measurements [17]. Some of these models are strong when applied in specific situations, while some may also be more widely applicable [12].

Important advantages of the model-based techniques are that they don't require extensive data, that the associated algorithms are simple, and that they are computationally cheap when making predictions [17]. Another important advantage is that the model-based techniques have a clear physical interpretation [12], and can thus be used to gain a deeper understanding of the underlying processes. Such insight can be used to not only solve the problem at hand, but also related problems. Downsides are that it is a non-trivial task to find an appropriate model, and that the model parameters need to be estimated. There is also a significant amount of signal processing that needs to be applied [17].

In the literature there are multiple uses of signal processing [17], [21]. These techniques are used for noise reduction, signal transformation, or signal extraction [17]. Noise reduction is used to remove outliers which would otherwise negatively impact performance. Signal transformation is used for time-frequency analysis [17]. Examples of signal transforms are Fast Fourier Transform (FFT), Short Time Fourier Transform (STFT), or Chirplet Transform [17], [21]. Signal extraction is used to extract useful signals, which can then in turn be processed further. Possible techniques are threshold or filtering based on frequency or power level, or compression based on PCA or SVD [17].

A second category of processing techniques are the learning-based ones. Learning-based techniques can be used to establish a link between the signals and the activities or entities that are being observed, if such signals contain patterns that are unique, differentiable, and consistent [12]. The learning-based algorithms can be divided into two categories: shallow learning and deep learning [17]. The advantage is that learning-based techniques can find patterns on their own, and that manually finding a model and parameters is not necessary. Some disadvantages are the need for training, that training can be costly, and that a large amount of data is required [17].

The category of shallow learning comprises techniques such as k-nearest neighbors (kNN), support vector machines (SVM), decision trees (DT), or naive bayes (NB) [17]. Data first needs to be pre-processed before it can be used as input for a shallow learning algorithm. Such pre-processing may be performed using dimensionality reduction (e.g. SVD or PCA), signal processing (FFT, STFT), or it may be done manually [17].

On the other hand we have the deep learning techniques, which comprise neural networks such as convolutional neural networks (CNN), recurrent neural networks (RNN) [17], long short-term memory (LSTM), and autoencoders [3]. Note that LSTMs are a form of RNN. The advantage of deep learning is that it requires minimal pre-processing of the input data [17], and that they are suited for large, complex datasets [3]. CNNs are regularly used for image processing and can be re-purposed to analyse CSI matrix data [17], or THz images [26]. RNNs and LSTMs can analyse sequences of elements and are thus suited to processing time series [17]. Savazzi et al. [15] anticipate that in the future CSI data will become more complex and high dimensional and they propose a suitable new neural network architecture.

In Ma et al. [17] there is also mention of *hybrid* techniques in which the model- and learning-based techniques are used together. In such a configuration a model-based algorithm may be used to extract course-grained information, and then a learning-based technique is used to refine the result.

VI. Alternatives

There exist alternative sensing technologies that do not make use of wireless sensing. We will give a number of such sensing technologies and compare them.

For localisation and tracking, one may make use of a satellite-based navigation system such as GPS. Such satellite systems provide accurate location estimates, but they have a number of downsides that make them difficult to use in certain situations [14]. The use of GPS requires that the targeted entity is carrying a device which is not always feasible [14], [16], and the use of GPS also significantly reduces the battery life, something that is unacceptable for IoT applications [14]. Additionally, obstacles and obstructions may disrupt the satellite connection [20].

Also commonly used are vision-based technologies which make use of a camera. The capturing of video material immediately raises some privacy questions [18], [22]. Additionally, such techniques require a significant amount of processing power [16], [22]. Vision-based solutions are also sensitive so occlusions and light conditions, which may be influenced by smoke, obstacles, weather conditions, time of day, and other factors [13], [16], [18], [21], [22].

Making measurements through the use of acoustics, such as ultrasound, is also a possibility. This has the advantage that it is low-cost and that it is sensitive to motion. The downside is that it is sensitive to background sounds and noise, and that the range is limited due to the attenuation of acoustic signals [13], [22].

In this paper we paid a lot of attention to device-free sensing, where the target is not wearing any sensors. It is, however, also possible to make measurements using sensors and to then transmit those measurements wirelessly [22]. The advantage is the high accuracy of the measurements that are made by such sensors [22]. Important downsides are that such sensors may be uncomfortable to wear, or that it is impossible for the target to wear any device or sensor at all [16], [22], [24].

Even though we pay a lot of attention to technology for measuring things, we must not forget that humans themselves are also capable of making measurements through human senses, such as vision and hearing. The advantage that this offers is simplicity and the fact that no technology is needed at all. The downside is that humans may be influenced by personal bias, previous experience, stress factors, or the limitations of human sensing [18].

Finally, we may list some inherent advantages of wireless sensing. Wireless sensing is often low-cost, is non-intrusive or even invisible to the targets, and may be deployed on a large scale over a wide area [3], [11], [18]. The associated hardware can be simple and commercially available [16], and may even be simple enough to not require specialised maintenance and installation [13].

VII. Challenges & future trends

In the literature [3], [13], [15]–[17], [22], [23] there is mention of the current challenges, and future trends. In this section we will present a number of them.

An important direction is the exploration of new frequencies that may be used for wireless sensing. Given the rapid expansion of IoT solutions, this may allow sensing systems to use *signals of opportunity* [16], or to use various sub-GHz bands [3]. Aernouts et al. [14] have demonstrated that it is feasible to use such sub-GHz signals originating from IoT devices. The introduction of 5G networks and future technology may produce more complex and large scale data [3]. We can thus see that future network technologies may introduce new opportunities for sensing.

Currently there are many experiments that are happening in laboratory environments [16]. Given that the environment has a significant impact on the performance and functioning of sensing systems [13], it is necessary to develop and test sensing systems in realistic scenarios in order to make them more robust [17]. Additionally, there are many systems that require extensive configuration when deployed and this makes adoption more difficult [23]. It is therefore necessary to develop sensing solutions that can be deployed in many environments without too much configuration.

As we said earlier, many experiments happen in controlled laboratory environments. Such experiments do not make use of real traffic, but are instead based on periodic pings [13]. In real life, wireless traffic is not constant and depends on the need of the connected devices [13]. Sensing solutions may also incur additional traffic and may therefore degrade network performance [17]. Finally, some Wi-Fi technologies that are used in communication networks such as beamforming, may make sensing more difficult [17].

Currently most sensing solutions only target one or a few people [23]. In order to use these solutions in realistic scenarios, it would be desirable to have sensing technology that can target multiple people. Currently there only exist a limited number of solutions that are indeed capable of performing sensing in multi-user environments [13].

Through the use of wireless sensing, it is possible to obtain sensitive information about people: identity, keystrokes, mobile phone passwords, and more [13], [23]. This makes such sensing systems an attractive target for criminals. Additionally, since wireless signals can travel through walls, and since wireless sensing is non-intrusive, the victims may not be aware that they are being targeted [13], [17]. Aside from collecting information, criminals may try to influence sensing systems through techniques such as bad data injection [3]. This can be dangerous since sensing solutions are being used for sensitive applications such as authentication and intrusion detection [13], [23]. Given these security threats, it is important that more efforts are made to secure wireless sensing systems [13].

VIII. Conclusion

In this overview paper we have discussed multiple aspects of wireless technologies that are present in the literature.

We started off by giving an historical overview of wireless sensing. We explained the development of wireless technologies, and their subsequent use in a number of historical applications. We also made the link between these historical applications and the more recent development of wireless sensing.

We reviewed multiple applications such as human presence detection, the localisation and tracking of humans and objects, the identification of humans and vehicles, and gesture and activity recognition. We have discussed healthcare solutions such as vital signs detection, heartbeat monitoring, respiration sensing, sleep analysis, gait analysis, elderly care, fall detection, and essential tremor detection. Agricultural applications, such as moisture detection in grain, and safety solutions, such as the detection of dangerous objects, were also mentioned.

A number of wireless technologies were considered, such as radar, Wi-Fi, 5G networks, and technologies related to the IoT. We listed the frequencies at which these technologies operate, and described a number of signal properties that can be recorded for further analysis. We also made mention of radar techniques that are based on time-of-flight and Doppler.

Next, we gave an overview of the processing techniques that can be utilised when analysing recorded signals. Here we made the distinction between model-based and learning-based techniques. We described theoretical and statistical models, and introduced both shallow and deep learning algorithms.

In order to compare wireless sensing to other sensing solutions, we list a number of such alternative solutions together with their respective advantages and disadvantages. We also make a case for wireless sensing by listing a number of inherent benefits.

Finally, we listed a number of challenges and future research trends. This includes the need to explore new frequencies and technologies such as the IoT, 5G networks, and sub-GHz frequencies. The need for more robust and configuration-free techniques was demonstrated, as well as the need to make wireless sensing compatible with real wireless traffic. Next, we paid attention to expanding the current sensing solutions, so that they can be applied to larger groups of targets. Lastly, we showed the vulnerability of wireless sensing with regards to security and privacy, given that wireless sensing can be used to eavesdrop and collect sensitive information, and given the vulnerability of sensing systems to malicious manipulation.

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